Measuring the Muon Content of Air Showers with IceTop

Javier G. Gonzalez

Before We Begin...

- IceTop detects the low energy muons far away from the shower axis (E > 200 MeV, r > 300 m).

- It is expected that the number of muons correlates with primary mass.

- The muon number is expected to scale roughly as a power of the primary energy:

$$N_\mu(r) \propto A \left(\frac{E}{A\epsilon_\pi} \right)^{p_\mu}$$

Mass number A, primary energy E, $p_\mu \sim 0.78$ (0.83 in Akeno)

- The muon lateral distribution can be parametrized in a standard (NKG-like) way. K. Greisen, Annu. Rev. Nucl. Sci. 1960.

- We will look at:
  - how one can estimate the muon lateral distribution function using IceTop,
  - the energy dependence of the muon density at a fixed reference radius for near-vertical events.
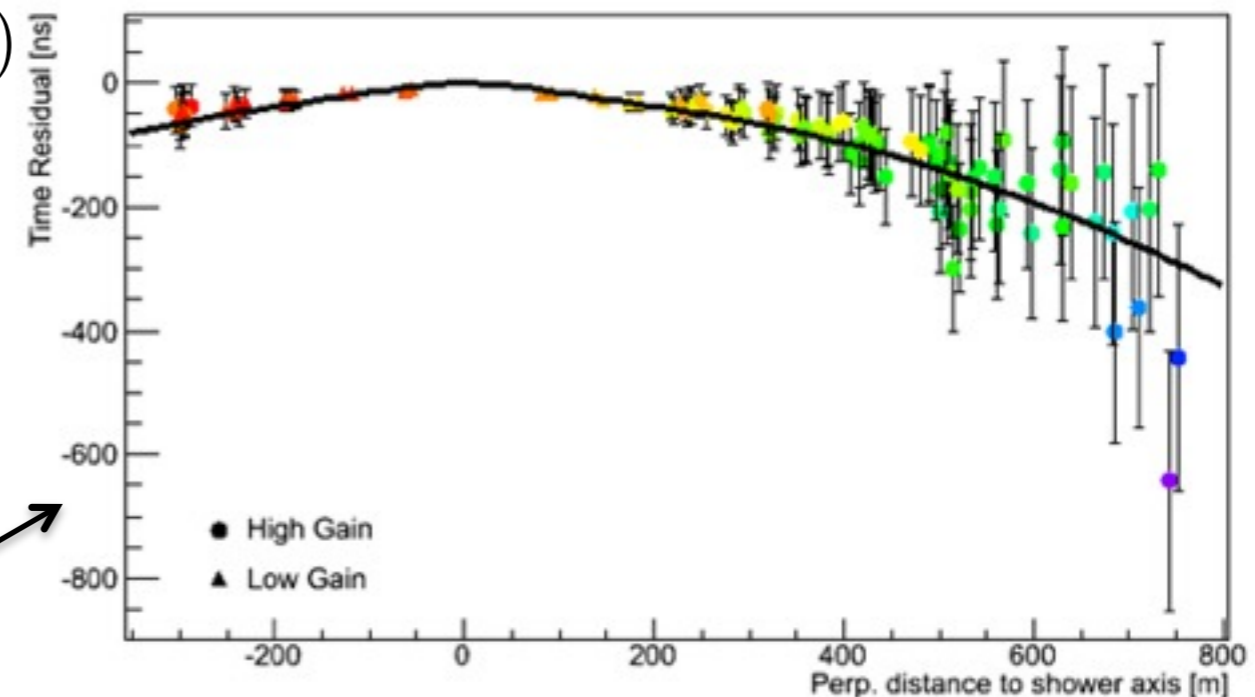
Tank pairs
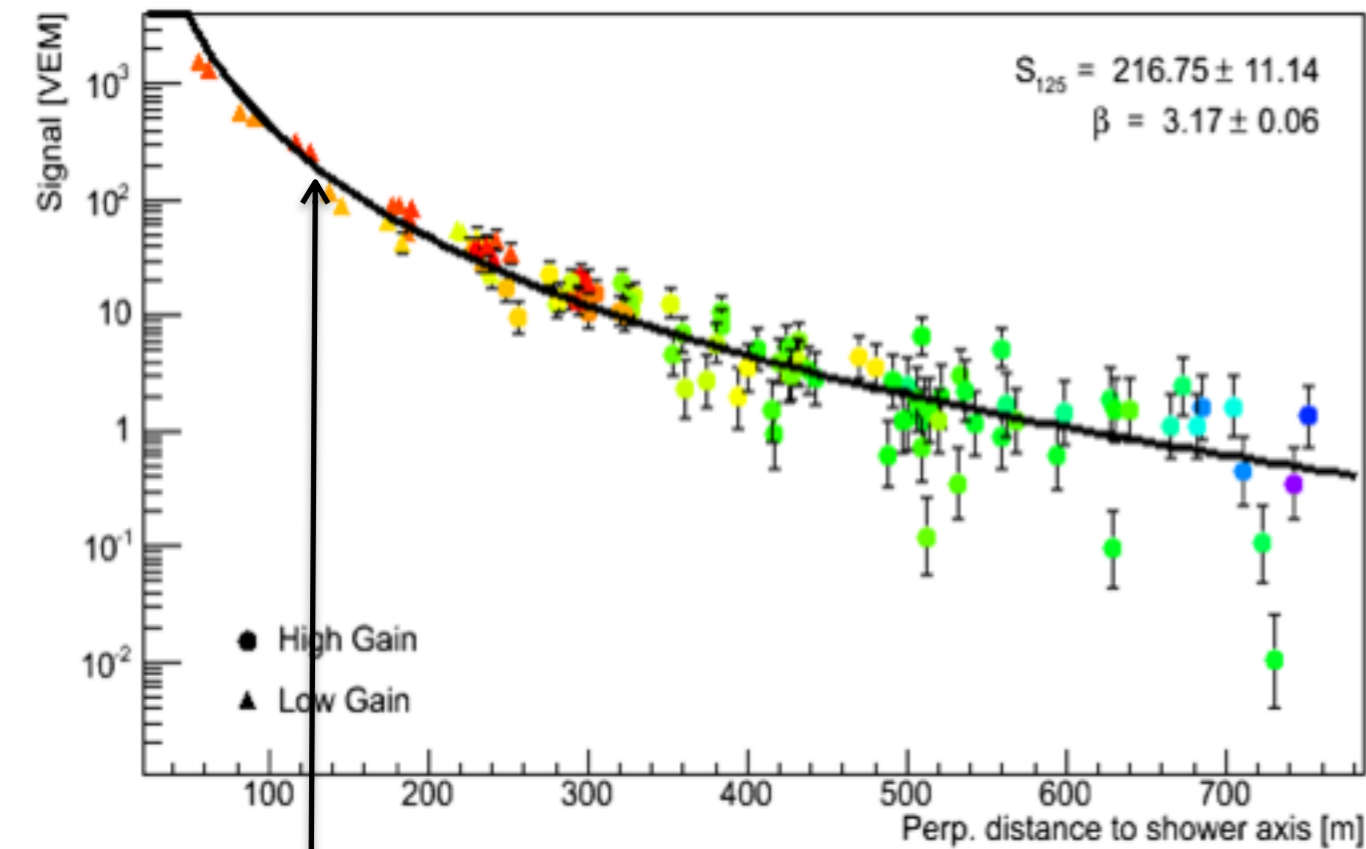
Run 116113 Event 62337765
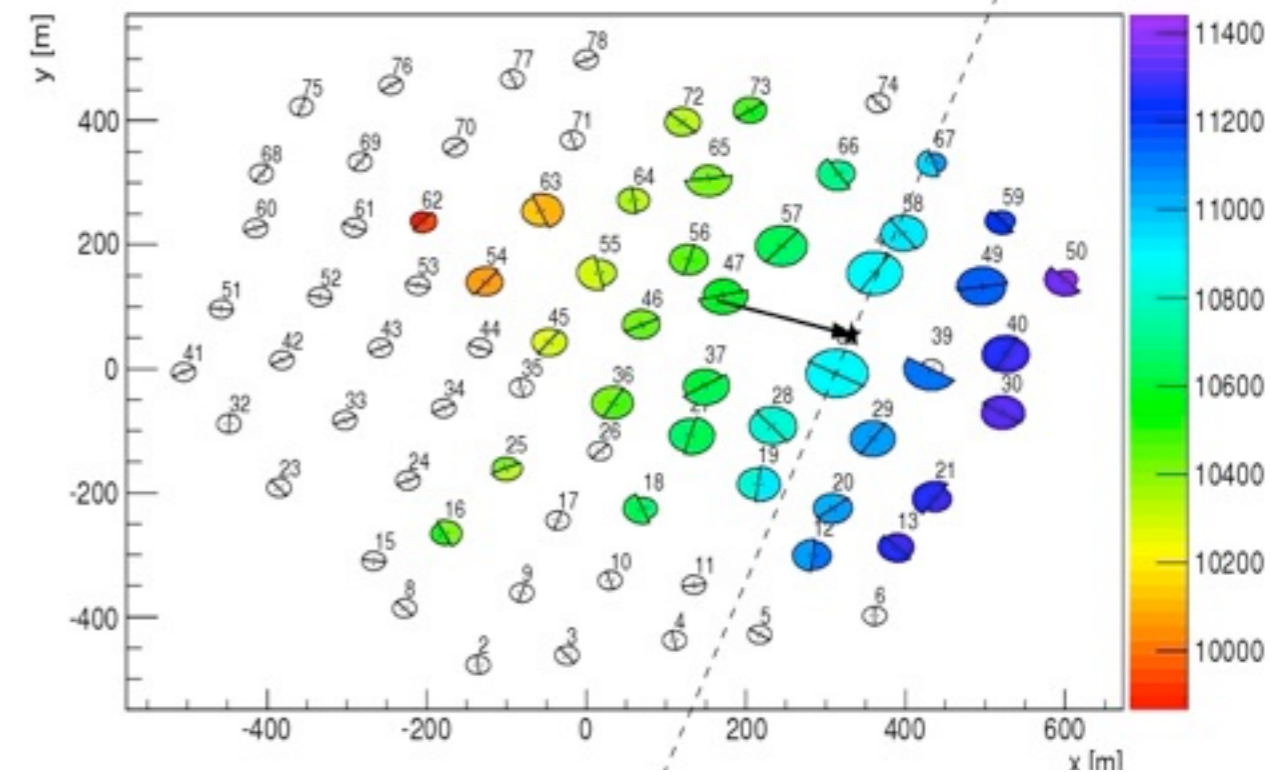
$$S(r) = S_{125}\left(e^{-\frac{d \sec \theta}{\lambda}}\right)\left(\frac{r}{125\,m}\right)^{-\beta - k \log\left(\frac{r}{125\,m}\right)}$$

Attenuation due to snow

$$t(\boldsymbol{x}) = t_0 + \left(\frac{\boldsymbol{x_c} - \boldsymbol{x}}{c}\right) \cdot \boldsymbol{n} + \Delta t(R)$$

$$\Delta t(R) = aR^2 + b\left(\exp\left(-\frac{R^2}{2\sigma^2}\right) - 1\right)$$

Reminder from B. Ruzybayev's talk

3

Single-tank Signal Calibration

(VEM Calibration)

muon peak position = 130.28 PE
1 VEM position = 123.77 PE
valley position = 91.01 PE
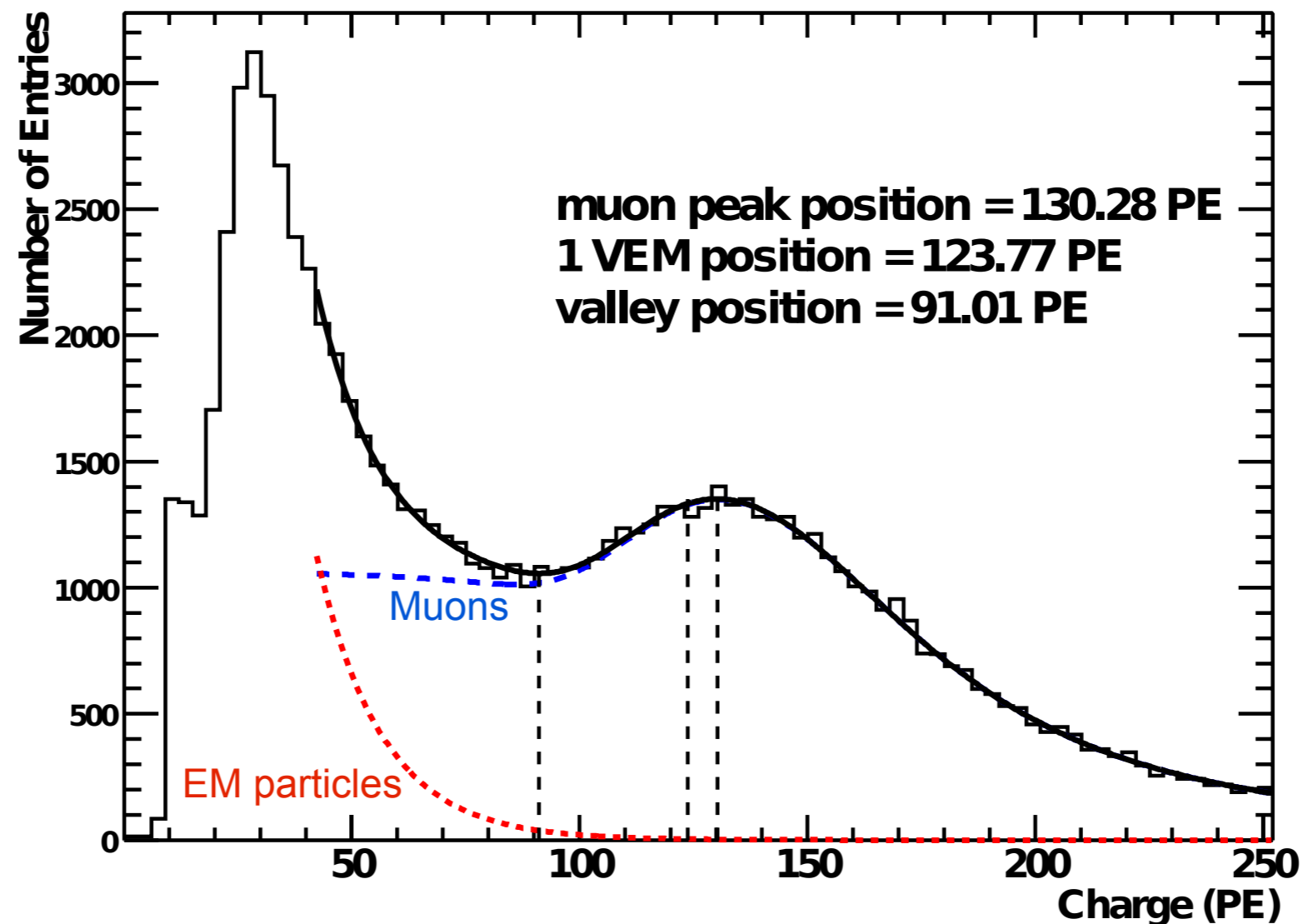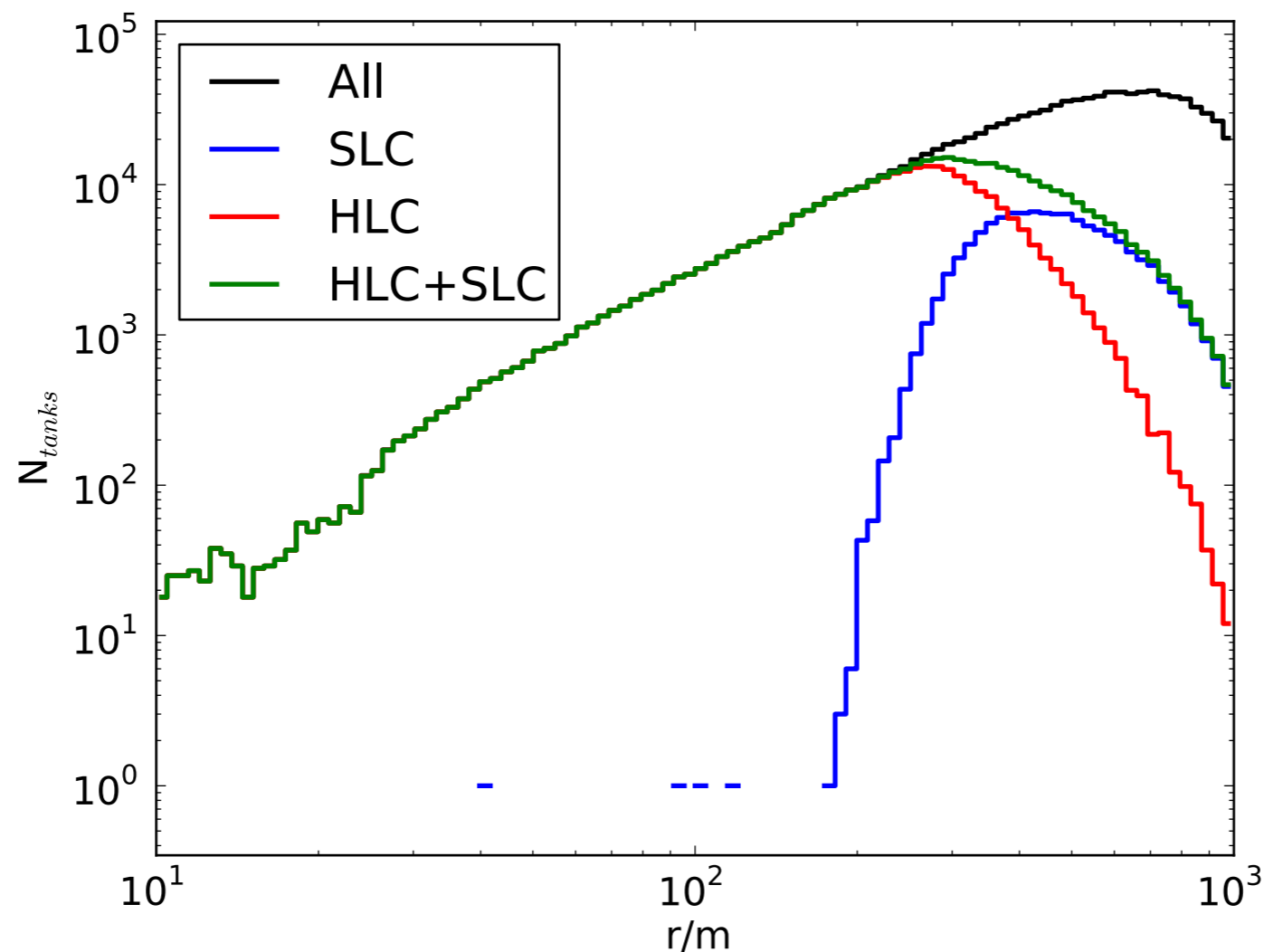
Example of a VEM calibration histogram for a particular tank, high-gain DOM in tank 61-A.
IceCube Collaboration, ICRC 2011, Beijing

4

Tank Distribution Relative to Shower Axis
($\theta < 6°$, E~10 PeV)

HLC: Tanks with signal whose partner within a station also has a signal
SLC: Tanks with signal whose partner within a station does not have a signal

Note that SLC tanks are relatively few and far from the shower axis.
Energy and direction reconstruction does not use SLC tanks at this time.

5

Charge-Distance to Axis Distribution

(only HLC)

IceCubePreliminary

$p_{trigger}$ drops below 1   Muon LDF starts to be seen
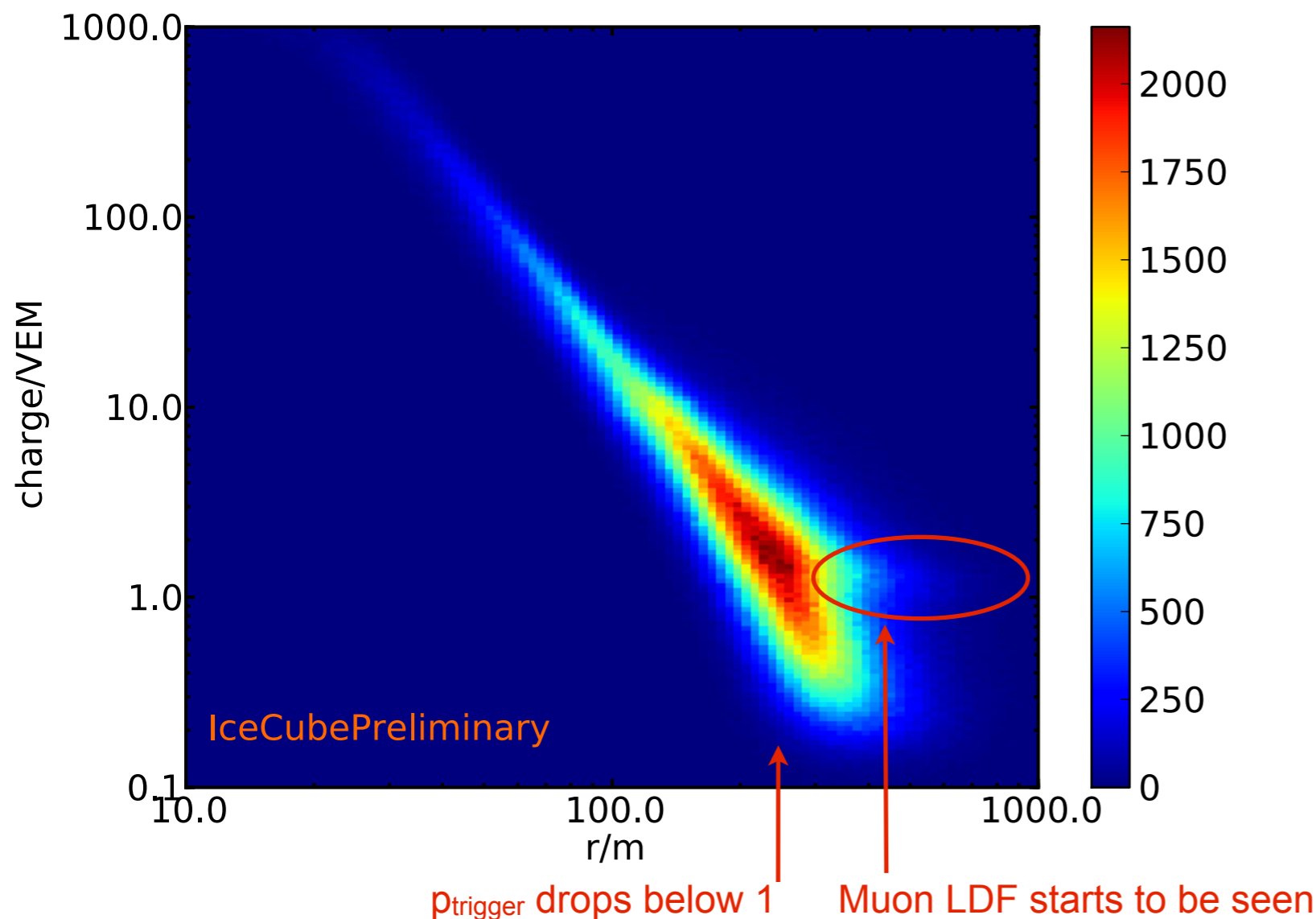
- IceTop 73-station configuration (June 1, 2010-May 13, 2011)

- All HLC tanks,

- Tank selection according to agreement with angular reconstruction. Time residual less than 1000 ns

- Selected events with 8 stations or more (16 tanks or more)

- No containment requirement

- 18 zenith bins from 0 to 70 degrees. roughly equally spaced in $sin(zenith)^2$

- 23 energy-bins from 1 to 200 PeV,

- 100 log(r) bins from 10 to 1000 m.

- Example of lateral charge histogram:
  - 10.0 PeV < E < 12.6 PeV
  - 28.1 < zenith < 31.7 degrees

6

Charge-Distance to Axis Distribution
(HLC and SLC)
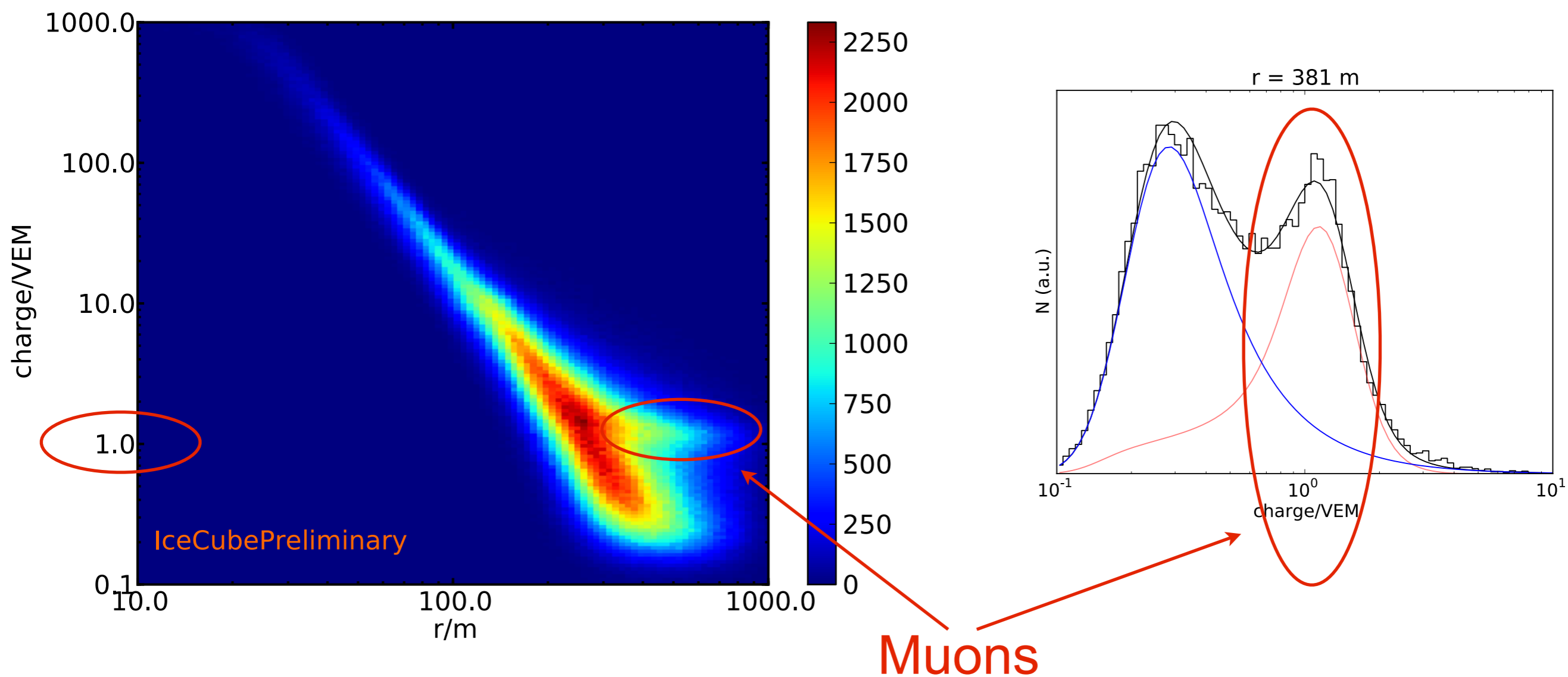
Muons

$28° < \theta < 32°$　　10 PeV < E < 12.6 PeV

Detector Response to Muons

given a zenith angle and expected number of muons

Single muons, various angles

	0.0°
	9.3°
	13.3°
	16.3°
	19.5°
	24.4°
	28.7°
	32.5°
	36.2°
	39.7°
	43.1°
	46.5°
	49.9°
	53.3°
	57.0°

Few muons, fixed angle (~10°)

	1 muons
	2 muons
	3 muons
	4 muons
	5 muons
	6 muons
	7 muons
	8 muons
	9 muons
	10 muons
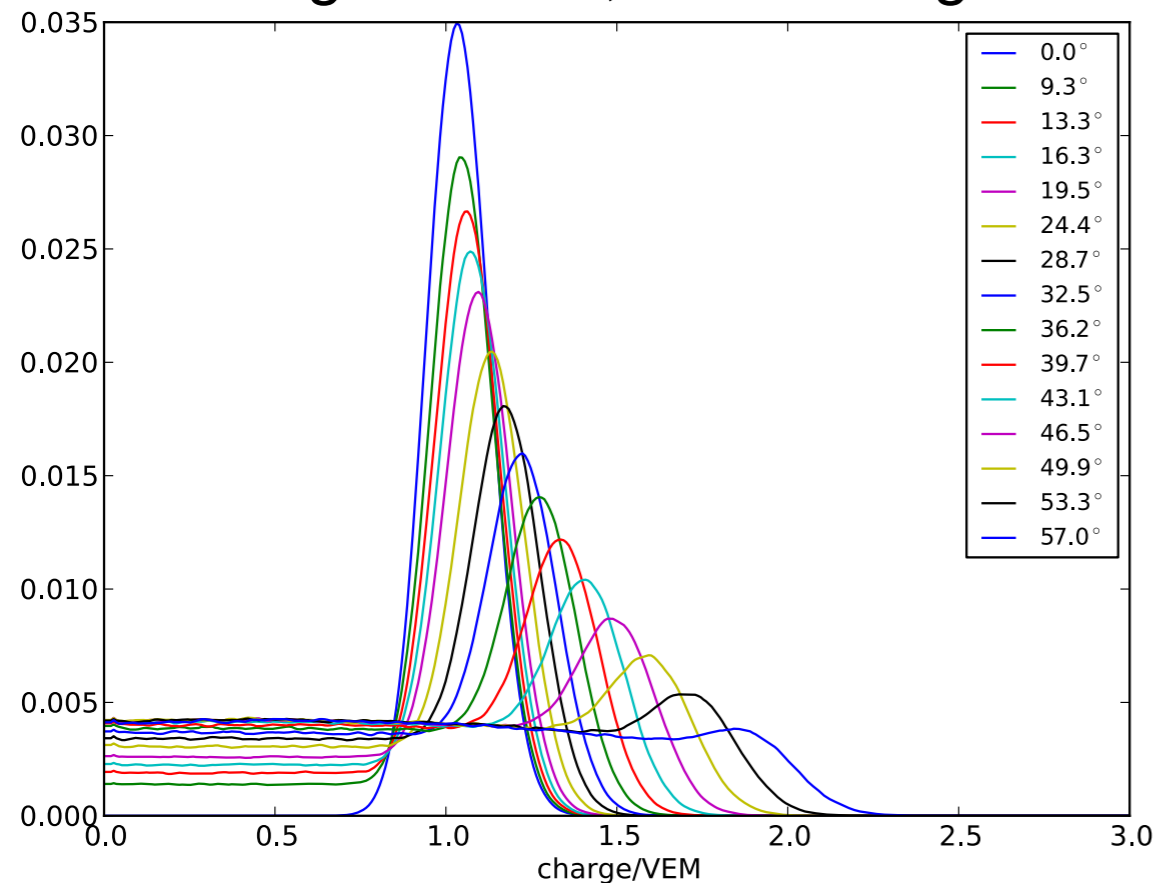
Response to single muons obtained from Geant4 simulations of IceTop detectors
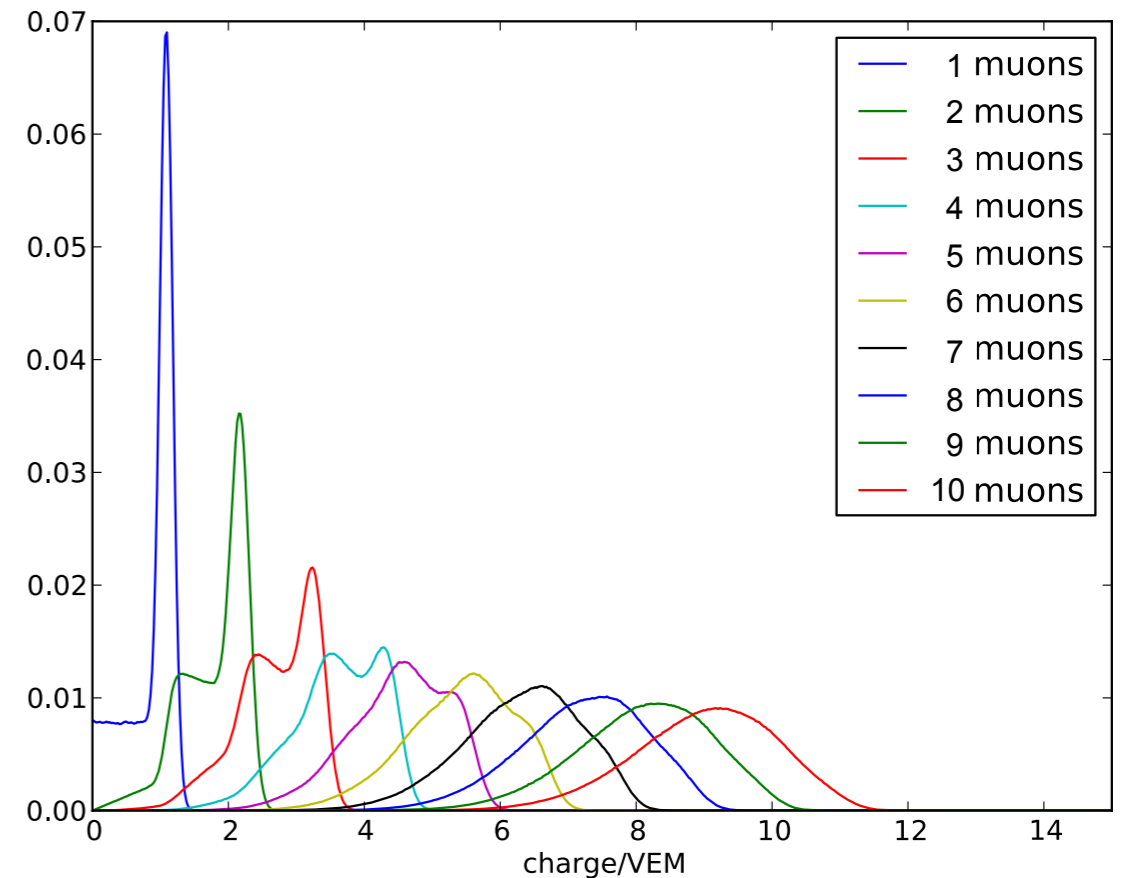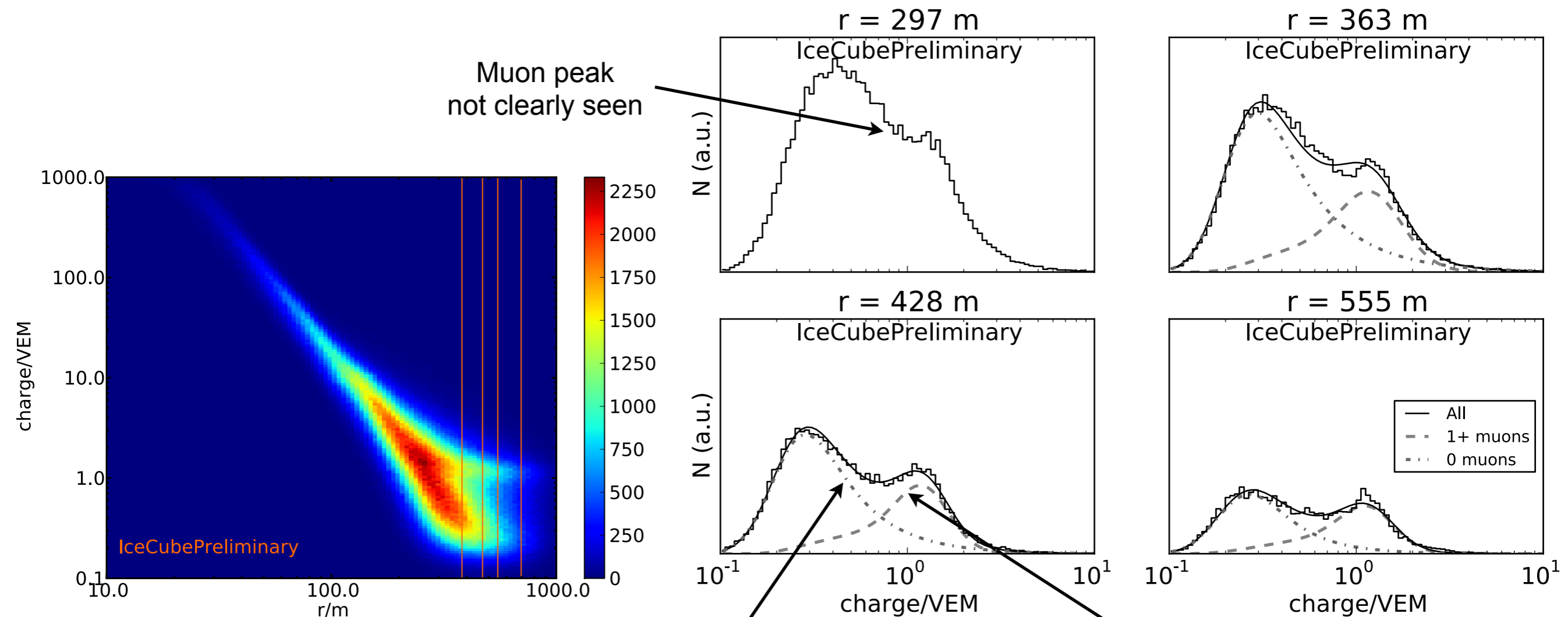
The response to n muons is the n-th order autoconvolution of the single-muon response

$$p(q|N_\mu, \theta) = \sum_n \frac{p^n e^{-\langle N_\mu \rangle}}{n!} p(q|n, \theta)$$

Expected number of muons

response to a number of muons

8

Charge Distributions at Different Radii

Muon peak not clearly seen

r = 297 m
IceCubePreliminary

r = 363 m
IceCubePreliminary

r = 428 m
IceCubePreliminary

r = 555 m
IceCubePreliminary

All
1+ muons
0 muons

Signal distribution for tanks detecting no muon
(Tail of the EM distribution)

Signal distribution for tanks detecting at least one muon

$$p_{\mu\,hit} = \frac{N_{\mu \geq 1}}{N_{tanks}}$$

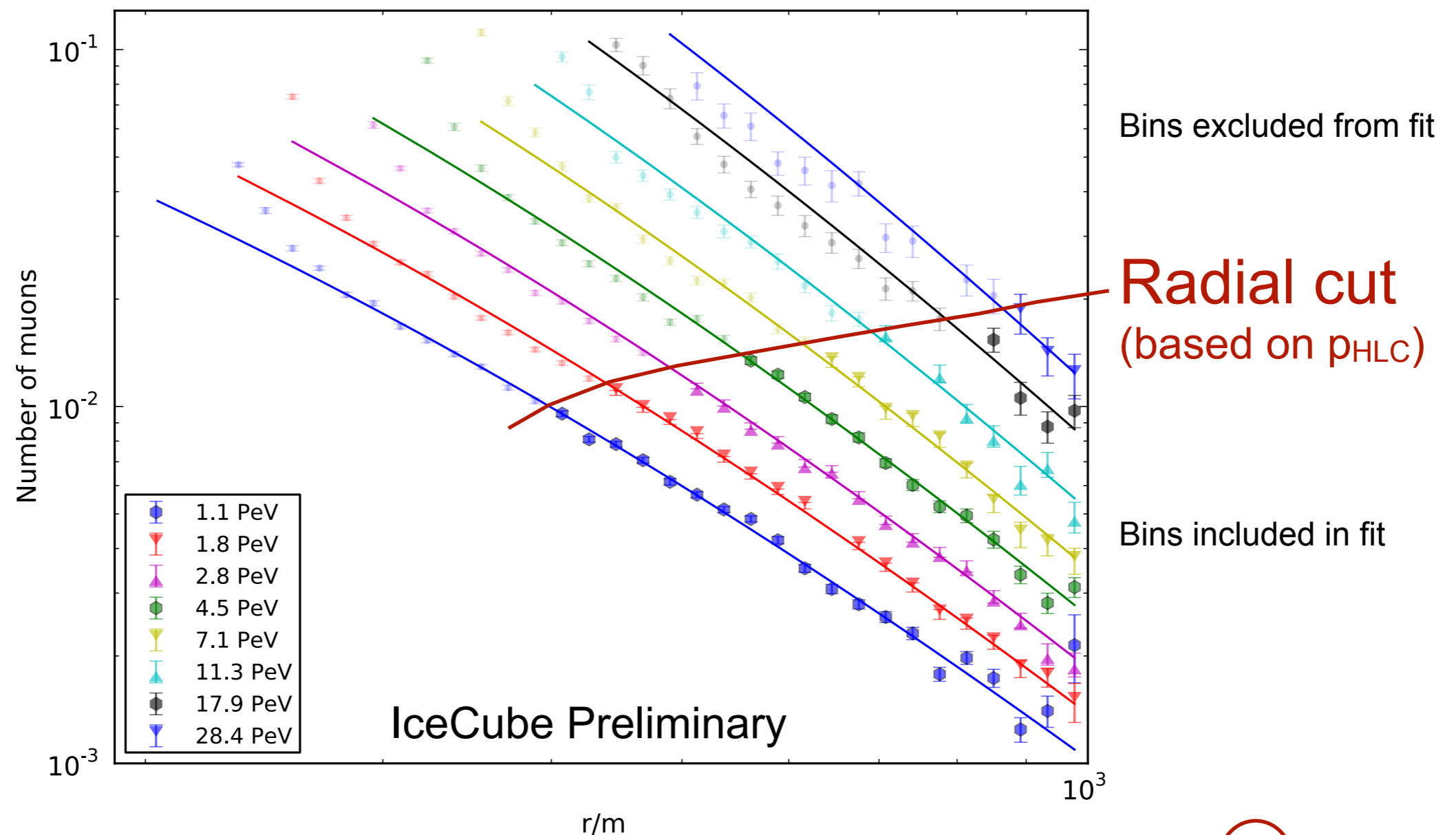$$= 1 - e^{-\langle N_\mu \rangle}$$

The muon response is widened and shifted to account for the EM component

A radial cut is required to decrease contribution from EM LDF

Muon LDFs at 0 degrees
(HLC and SLC)

Bins excluded from fit

Radial cut
(based on p_{HLC})

Bins included in fit

IceCube Preliminary

Legend:
- 1.1 PeV
- 1.8 PeV
- 2.8 PeV
- 4.5 PeV
- 7.1 PeV
- 11.3 PeV
- 17.9 PeV
- 28.4 PeV

Number of muons (y-axis), r/m (x-axis)

Two free parameters
(the rest are set to Greisen's values)

$$N_\mu(r) = N_{r_0} \, r^{-0.75} \left(\frac{320\,\mathrm{m} + r}{320\,\mathrm{m} + r_0} \right)^{-\gamma}$$
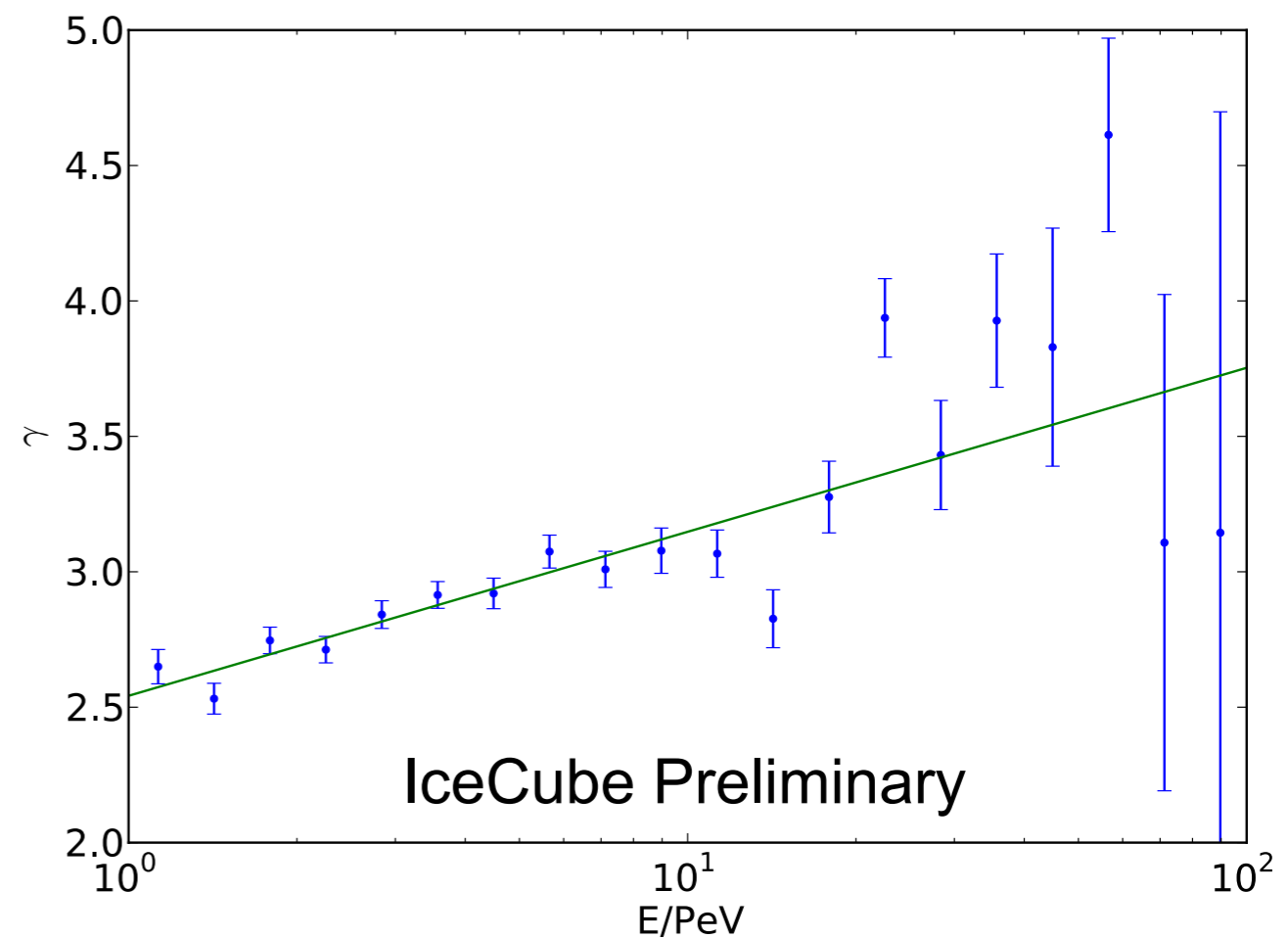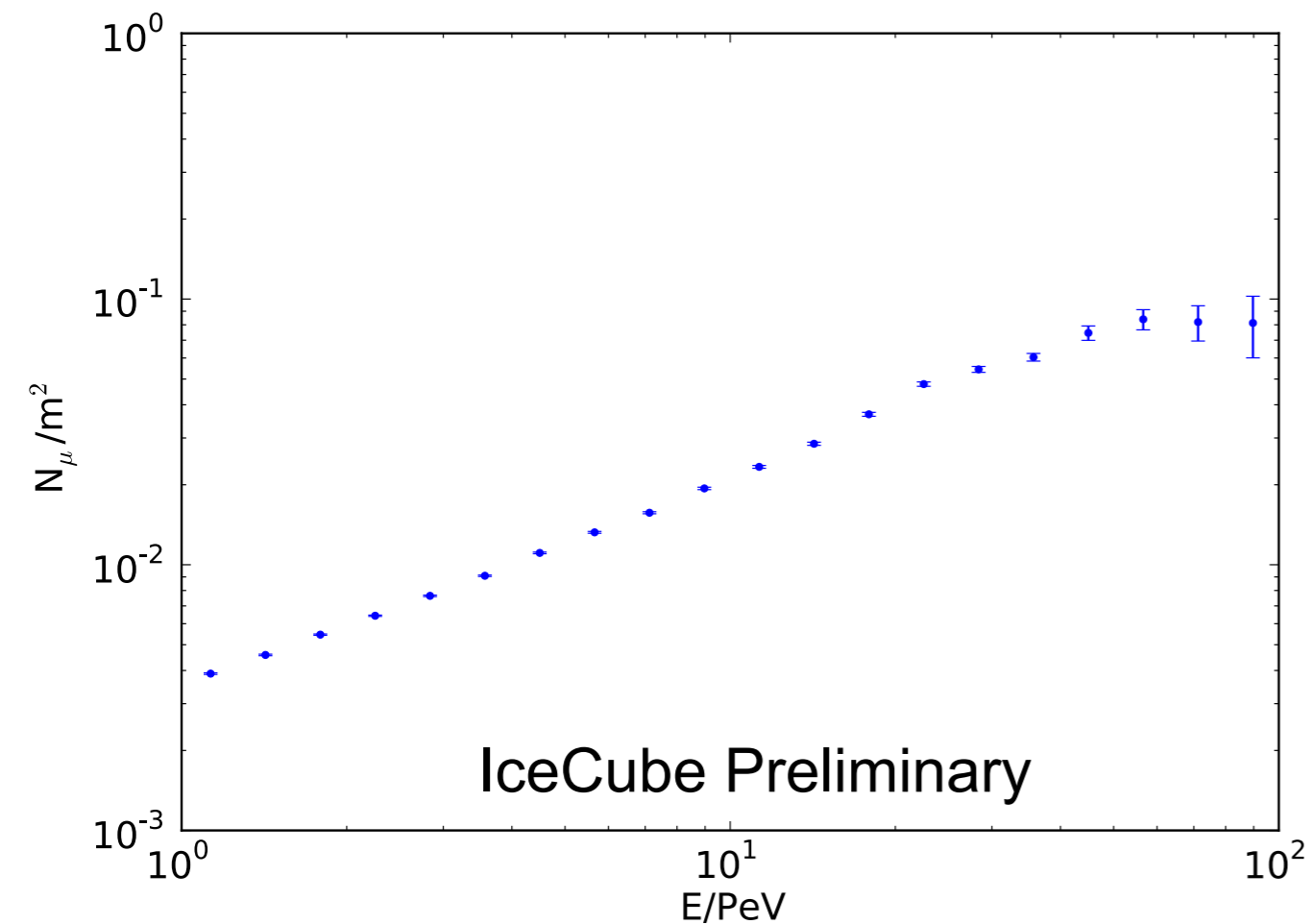
10

Muon LDF Parameters
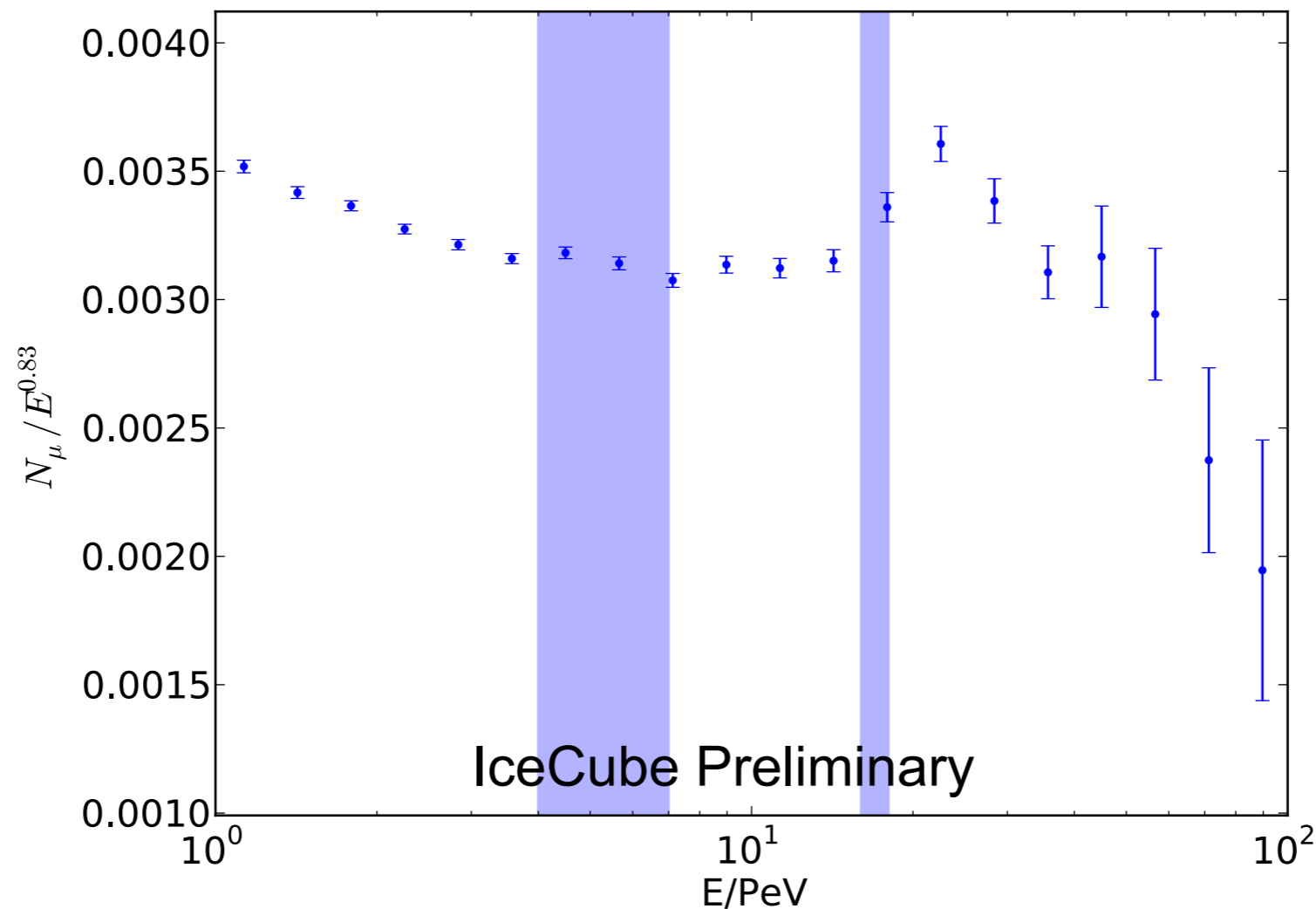
$$\theta < 6°$$

N$_{600}$ γ

N$_{600}$ scales geometrically as expected

$$\gamma_0 = p_0 + p_1 \log_{10}(E/PeV)$$

11

Deviations from a Power Law

$$\theta < 6°$$

- The resulting N_{600} weighed by $E^{0.83}$ to enhance the features.
  The choice of 0.83 comes from M. Nagano et al. J. Phys. G 10 (1984).

- Colored regions correspond to the location of spectral features
 in primary energy spectrum (see B. Ruzybayev's talk). Just for reference!

Conclusion

- With IceTop we can measure the average number of muons at large distances from the shower axis. We use 600 m as reference distance at this time.

- The dependence of muon number N_{600} as a function of energy shows departures from a power law.

- We draw no conclusion regarding primary composition at this time.

- In order to make quantitative statements regarding the attenuation of the muon component, its zenith angle dependence, and its relation to primary composition, a new reconstruction procedure is being developed.

- The extent to which we can estimate the number of muons event by event is under study.

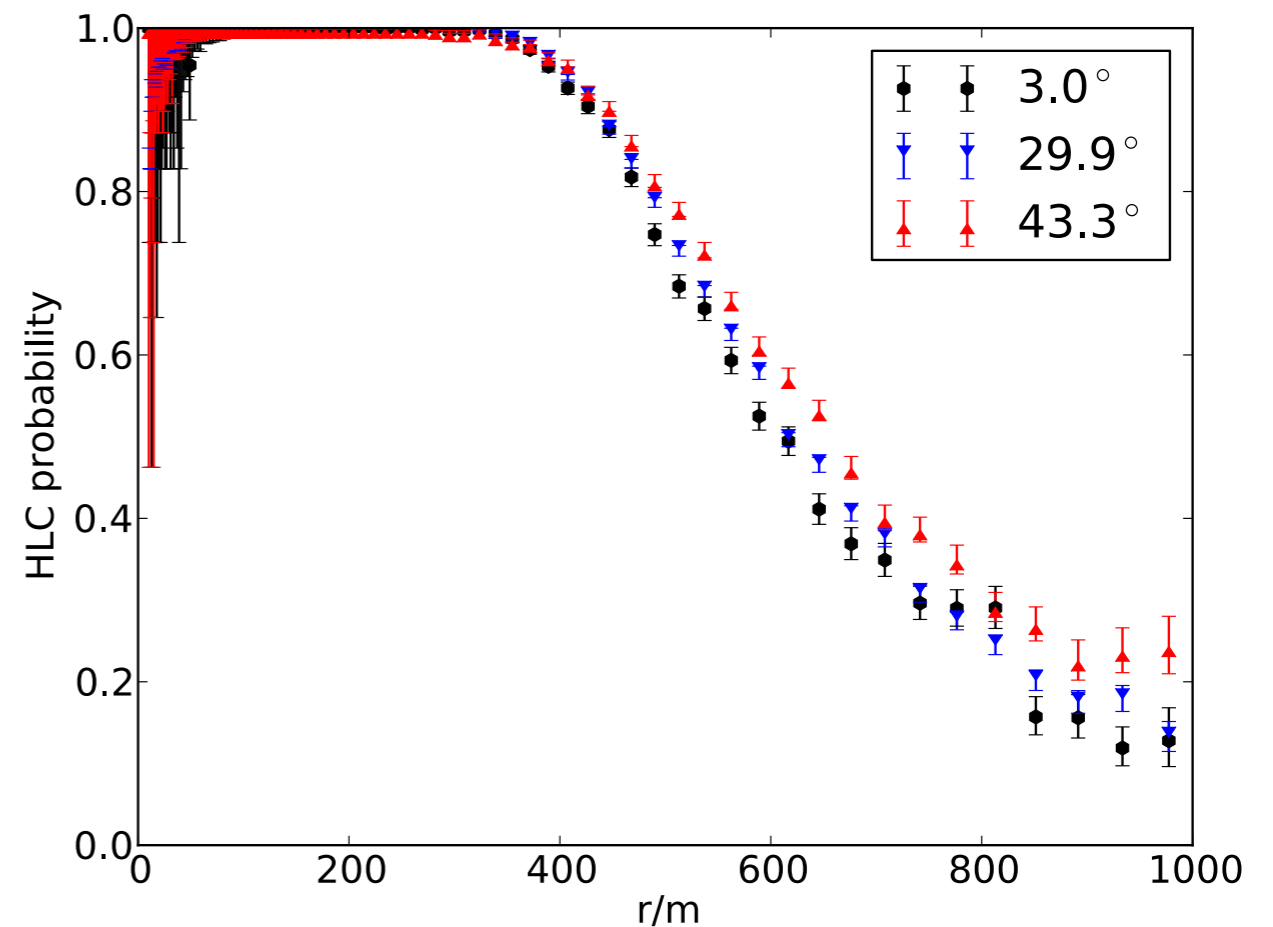- It is perhaps worth considering the use of this technique in similar air shower arrays.
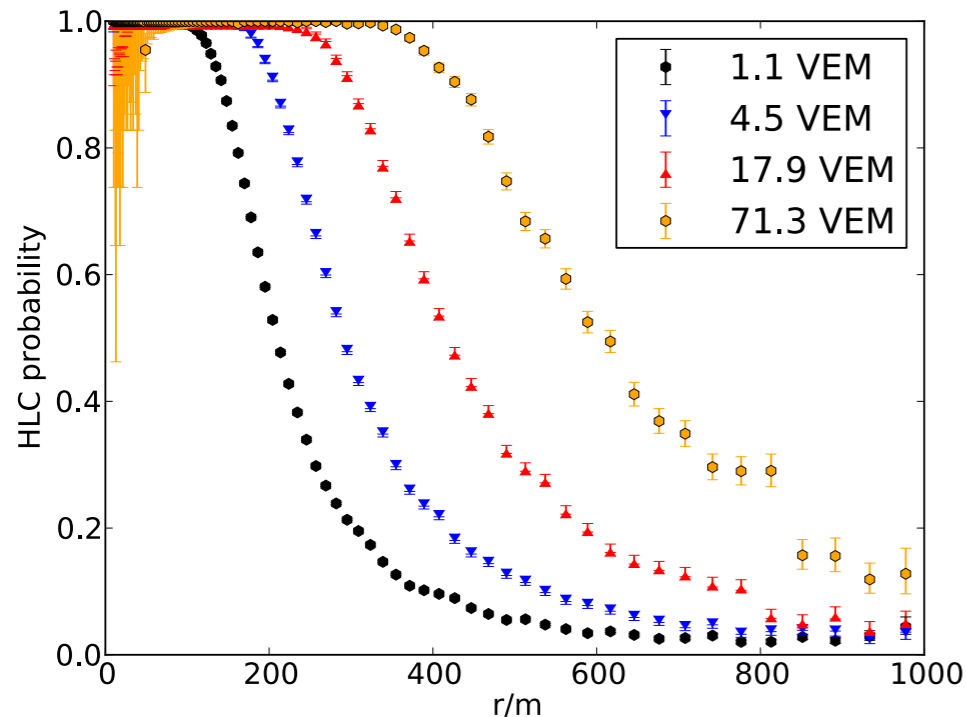
Defining a Radial Cut
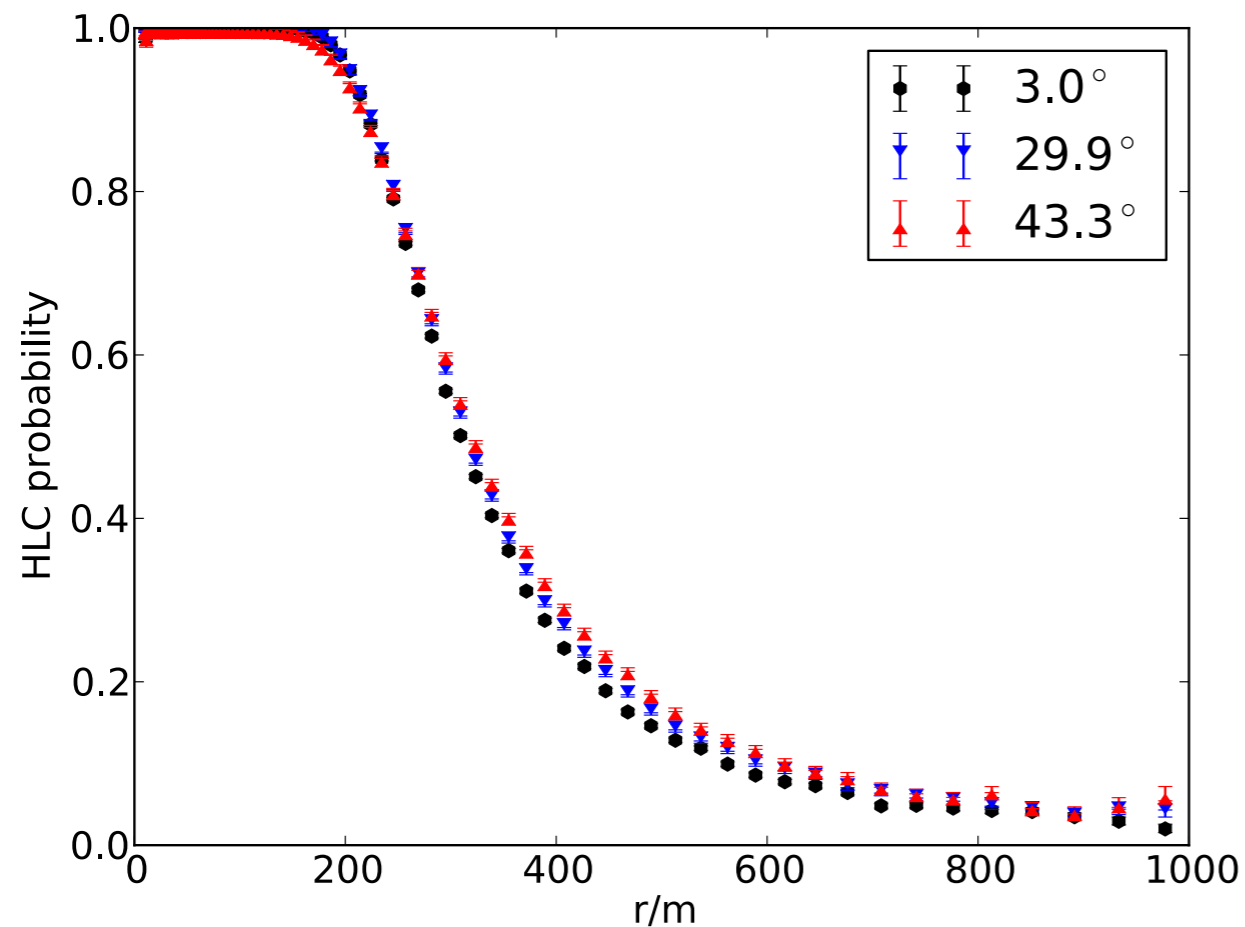
p_{HLC}: The probability that the partner of a given tank with signal also has a signal.

It can be determined from data (from slide 4) and
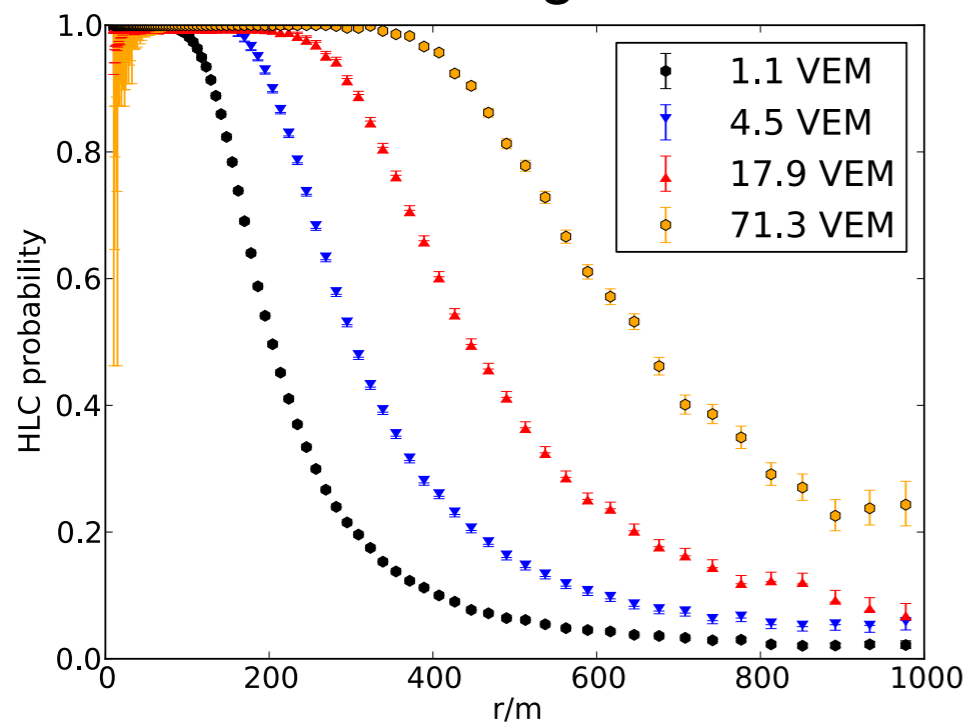does not to depend strongly on zenith angle, only on s_{125}.
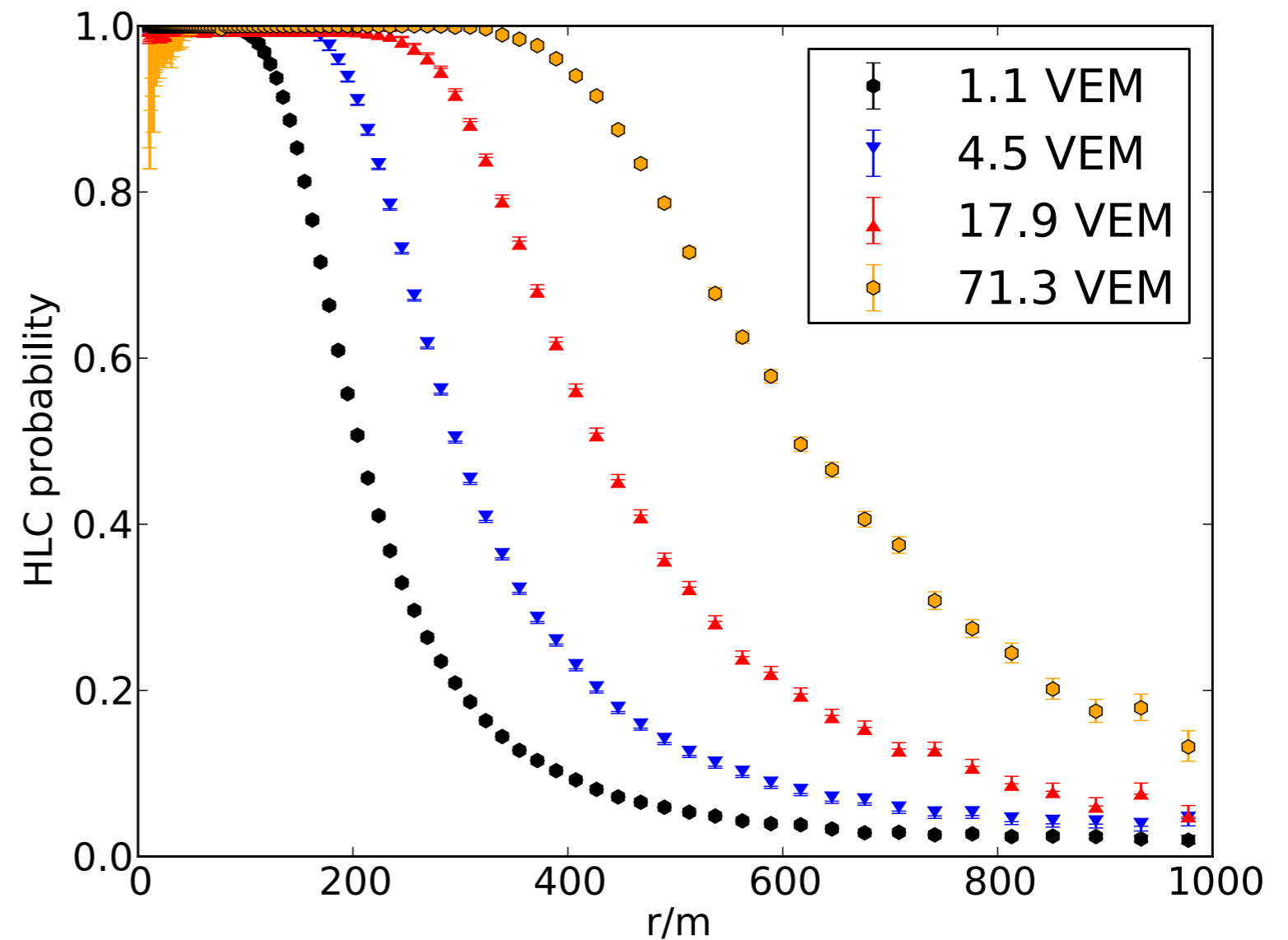
Lateral HLC Probability

The radial cut is such that $p_{HLC} < 0.1$ at 30 degrees.